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PERFORMANCE GAINS BY USING HEATED NATURAL-GAS FUEL IN AN ANNULAR TURBOJET COMBUSTOR

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16. Abstract

A full-scale annular turbojet combustor was tested with natural-gas fuel heated from ambient temperature to 800 K (980° F). In all tests, heating the fuel improved combustion efficiency. Two sets of gaseous fuel nozzles were tested. Combustion instabilities occurred with one set of nozzles at two conditions: one where the efficiency approached 100 percent with the heated fuel; the other where the efficiency was very poor with the unheated fuel. The second set of nozzles exhibited no combustion instability. Altitude relight tests with the second set showed that relight was improved and was achievable at essentially the same condition as blowout when the fuel temperature was 800 K (980° F).

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PERFORMANCE GAINS BY USING HEATED NATURAL-GAS FUEL IN AN ANNULAR TURBOJET COMBUSTOR

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SUMMARY

A test program was conducted to evaluate the effect of heated natural gas on combustor performance. The combustor was tested at two off-design conditions where the efficiency was known to be less than 100 percent with ambient-temperature fuel. Two fuel nozzle configurations were tested: a pintle nozzle and a showerhead nozzle.

In all tests, heating the fuel improved combustion efficiency. Efficiency gains were highest with the pintle nozzles. However, combustion instabilities occurred with these nozzles at two conditions: one where the efficiency approached 100 percent with the heated fuel; the other where the efficiency was very poor with unheated fuel. Also, the rate of change of combustion efficiency with fuel temperature was very high at the most severe test condition with near-ambient-temperature fuel.

Combustion with the showerhead fuel nozzles was stable over all test conditions. Efficiency gains were moderate but discernible. Altitude blowout and relight tests with these nozzles showed that significant gains in altitude performance are possible if the fuel is heated to 800 K (980° F). At this fuel temperature, relight was achieved at the same airflow condition as blowout.

INTRODUCTION

This report describes efforts made to improve combustor performance with natural-gas fuel at severe operating conditions by heating the fuel. Two types of fuel injectors were used to determine the effect of injection configuration.

Liquified natural gas as a fuel for turbojet engines powering a supersonic transport has been shown to have many advantages over the conventional ASTM A-1 kerosene-type fuel (refs. 1 to 3). Some of the reported advantages are increased heat-sink capacity, higher heating value on a weight basis, low flame radiation, low smoke levels, and a reduced tendency for fuel decomposition. Natural gas has demonstrated good performance in turbojet engines used for ground power applications.

Previous tests with a combustor designed for a supersonic engine have demonstrated performance with natural-gas fuel equal to that of ASTM A-1 liquid fuel at simulated takeoff and cruise conditions (ref. 4). However, combustor performance at off-design conditions was considerably poorer with natural-gas fuel (ref. 5). Combustion efficiency with natural gas decreased with decreasing combustor pressure and was particularly sensitive to decreasing inlet-air temperature. Of particular importance were the poor altitude blowout and relight limits obtained with natural-gas fuel. For every operating condition, the blowout and relight pressures were significantly higher than those obtained with ASTM A-1.

This investigation was conducted to demonstrate the performance gains possible with heated natural-gas fuel. No attempt was made to alter the basic combustor geometry. Two fuel nozzles were tested to determine whether the effect due to fuel heating varied significantly with nozzle configuration. Fuel at temperatures to 800 K (980° F) was tested.

The combustor was tested at two off-design conditions. The airflow and inlet-air temperature were held constant at 20.6 kilograms per second (45.5 lb/sec) and 422 K (300° F), respectively. The diffuser inlet total pressure was set at 17.2 or 13.8 N/cm^2 (25.0 or 20.0 psia). The change in inlet total pressure produced a corresponding change in combustor reference velocity from 32.3 meters per second (106 ft/sec) to 40.5 meters per second (133 ft/sec). The combustor was tested over a range of fuel-air ratios from 0.01 to 0.02.

FACILITY AND INSTRUMENTATION

Testing was conducted in a closed-duct test facility of the Engine Components Research Laboratory of the Lewis Research Center. A block diagram of this facility is shown in figure 1. A detailed description of the facility and instrumentation is contained in reference 6. All fluid flow rates and pressures are controlled remotely. Combustor exit temperatures are measured at 3° increments around the circumference with three five-point aspirated thermocouple probes which traverse circumferentially in the exit plane. Five hundred and eighty-five individual exit temperatures are used in each mass-weighted average exit temperature calculation.

Fuel for the pintle nozzle tests was heated by a natural-gas-fired heat exchanger capable of raising the temperature of fuel flowing at 0.45 kilogram per second (1.0 lb/

sec) from 300 to 600 K (80° to 620° F). The fuel heater was then modified to raise the temperature of the same quantity of fuel from 300 to 800 K (80° to 980° F). The shower-head nozzle tests were then conducted with the modified heat exchanger set at the higher temperature.

Test Combustor

The combustor tested was designed using the ram-induction approach and is described in reference 7. With this approach the compressor discharge air is diffused less than it is in conventional combustors. The relatively high-velocity air is captured by scoops in the combustor liner and turned into the combustion and mixing zones. Vanes are used in the scoops to reduce pressure loss caused by the high-velocity turns. The high velocity and the steep angle of the entering air jets promote rapid mixing of both the fuel and air in the combustion zone and of the burned gases and air in the dilution zone. The potential result of rapid mixing is a shorter combustor or, alternatively, a better exit temperature profile in the same length.

A cross section of the combustor is shown in figure 2. The outer diameter is almost 1.07 meters (42 in.) and the length from compressor exit to turbine inlet is approximately 0.76 meter (30 in.). A snout on the combustor divides the diffuser into three concentric annular passages. The central passage conducts air to the combustor headplates and the inner and outer passages supply air to the combustor liners. There are five rows of scoops on each of the inner and outer liners to turn the air into the combustion and dilution zones.

The snout and the combustor liners are shown in figure 3. Figure 3(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liner can be seen, as well as the openings in the headplate for the fuel nozzles and swirlers. Figure 3(b) is a view of the snout and the upstream end of the combustor liner. The V-shaped cutouts in the snout fit around struts in the diffuser. The circular holes through the snout walls are for the fuel nozzle struts. Figure 3(c) gives a closer view of the liner and headplate, showing the fuel nozzles and swirlers in place. There are a total of 24 fuel nozzles in the combustor. Fuel temperature was measured in the manifold supply to the fuel nozzles.

Fuel Nozzles

Figure 4 shows the fuel strut and fuel-nozzle - air-swirler assemblies. Two fuel nozzles were tested. Both nozzles were adapted to the fuel strut, which was originally designed to handle liquid fuel.

The pintle fuel nozzle (fig. 4(b)) was designed to be interchangeable with the liquid fuel nozzle. This nozzle injects the fuel as a hollow cone into the combustion chamber. Because of the nozzle installation procedure, the pintle could not extend downstream beyond the air swirler. Furthermore, since the airswirler screwed on over the fuel nozzle strut, the maximum pintle diameter was limited by the hole in the air swirler. A larger pintle surface may be desirable to enhance flame seating and combustion stability at high fuel-air ratios.

The showerhead fuel nozzle (fig. 4(c)) injects the fuel as six discrete jets into the combustor and was designed to provide a lower fuel injection velocity. This is accomplished by providing a larger injection area downstream of the air swirler. The fuel strut is assembled with the adapter piece into the combustor in the same manner that the pintle nozzle is assembled. The showerhead fuel nozzle is then screwed into the combustor fuel strut assembly and safety-wired in place.

Because the fuel strut was originally designed for use with liquid fuel, the small 0.45-centimeter- (0.18-in.-) diameter feed hole through the struts accounts for the major flow restriction in the fuel system. The manifold-pressure-against-fuel-flow characteristics for both nozzles were therefore similar. Total fuel flow as a function of manifold pressure for a range of fuel temperatures is shown in figure 5. From the slope of the curves, it can be inferred that the flow chokes in the fuel strut at all test conditions.

Fuel

The chemical and physical properties of the natural-gas fuel are presented in table I. The natural-gas composition reported is representative of the natural gas used during the test program. The gas composition did vary slightly and is dependent upon the season, the demand, and the gas field from which it is obtained.

TEST CONDITIONS

The combustor was tested with both gas nozzles at two severe operating conditions where the combustion efficiency with ambient fuel was known to be less than 100 percent. In this way the effect of heated fuel on combustion efficiency may be discerned. The test conditions are shown in table II. A measure of the severity of combustion, the product of combustor inlet pressure and temperature divided by the reference velocity (PT/V), is also shown (the lower the number, the more severe the condition). The inlet airflow and temperature were maintained constant at nominally 20.6 kilograms per second (45.5 lb/sec) and 422 K (300° F), respectively. Data were taken over a range of fuel-air ratios from 0.01 to 0.02. Some data taken at these conditions with fuel at ambient temperature (approximately 300 K (80° F)) were previously reported in reference 8.

Altitude blowout and relight tests were conducted with the showerhead gas nozzles only. These tests were made with ambient fuel and with fuel heated to about 800 K (980° F). The combustor inlet-air temperature was approximately 300 K (80° F). A combustor reference Mach number of 0.075 was arbitrarily chosen and was held constant by varying the airflow with combustor pressure. The facility is capable of reducing the combustor pressure to approximately 1 N/cm^2 (1.5 psia). With fuel temperatures of 800 K (980° F), spontaneous ignition was not expected in these tests. Fuel flow was maintained constant at approximately 0.125 kilograms per second (0.276 lb/sec). Combustor blowout was defined as the combustor inlet total pressure below which a temperature rise of 90 K (162° F) could not be maintained.

RESULTS AND DISCUSSION

Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. The exit temperature was measured by the three five-point traversing aspirated thermocouple probes and was mass weighted for the efficiency calculation. The theoretical temperature rise included the increase in enthalpy due to heating the fuel.

Pintle Nozzles

The effect of heated fuel on efficiency for the pintle nozzles at the two test conditions is shown in figures 6 and 7. Figure 6 shows efficiency as a function of fuel-air ratio for various fuel temperatures. Figure 7 is a cross plot of the data from figure 6 to show the effect of fuel temperature on combustion efficiency at fuel-air ratios of 0.01, 0.015, and 0.02. A combustion instability of approximately 250 hertz occurred in the first test condition at high fuel-air ratios where the efficiency approached 100 percent. No data were taken in the region of unstable operation and consequently there is no curve for the 0.02 fuel-air ratio in figure 7(a).

Some of the data shown in figure 6 taken at the second test condition were previously reported in reference 8. The fuel temperature was approximately 300 K (80° F). Poor combustor performance was obtained at this condition and a combustion instability was encountered at a fuel-air ratio of 0.0164. The instability was not encountered when additional data were taken for the heated-fuel program.

Since the fuel flow chokes in the fuel strut, the instability was not attributed to coupling with the fuel system. The combustion instability encountered with poor efficiency at the second condition is probably caused by a different initiating mechanism than the combustion instability encountered with good efficiency at condition 1. Both instabilities, however, indicate that the pintle nozzle geometry of injection used in these tests may be unsuitable for gaseous fuel in terms of hardware fatigue.

Figure 7(a) shows that, at the first test condition, combustion efficiency increases with increasing fuel temperature over the range of operating conditions and fuel-air ratios tested. Efficiency is between 90 and 100 percent, so only a slight increase in efficiency with fuel temperature is discernible. In figure 7(b), a larger effect is observed at the more severe second condition. A rapid rise in efficiency with fuel temperature occurs between 300 and 400 K (80° and 260° F). There is a less rapid increase in combustion efficiency at the higher fuel temperatures. The steep slope of the 0.01 and 0.015 fuel-air ratio curves in figure 7(b) near ambient fuel temperature indicates that small variations in fuel temperature will produce large variations in combustor performance at this condition for operation at these fuel-air ratios. The instability encountered in previous tests (ref. 8), although not encountered in these tests, is therefore not unexpected. Significant improvement in combustion efficiency is obtained by heating the fuel to 500 K (440° F) at this condition.

Showerhead Nozzles

The effect of heated fuel on efficiency for the showerhead nozzles at the two test conditions is shown in figures 8 and 9. Figure 8 shows efficiency as a function of fuel-air ratio for various fuel temperatures. Figure 9 is a cross plot of the data from figure 8 to show the effect of fuel temperature. Combustion efficiency increases with increasing fuel temperature over the range of test conditions and fuel-air ratios tested. Efficiency at the first condition is between 85 and 95 percent with this nozzle, so that only a slight increase in efficiency with fuel temperature is discernible - as was found with the pintle nozzles at this condition. However, no large effect is observed at the more severe second condition with the showerhead nozzles, especially between 300 and 400 K (80° and 260° F), where the largest change occurred with the pintle nozzles.

No combustion instability was encountered in tests with the showerhead nozzles. This method of fuel injection appeared to be one of the most stable, as reported in reference 8. This stability may also be responsible for a less dramatic increase in combustor performance with increasing fuel temperature.

Figures 6 and 8 show that, at the more severe second test condition, this combustor has a minimum value of combustion efficiency with ambient temperature fuel at a fuel-air ratio of approximately 0.013 for both fuel nozzles tested. This phenomenon is probably caused by the combustor geometry. This depression in efficiency is more pronounced with the pintle nozzles than with the showerhead nozzles. Raising the fuel temperature to 800 K (980° F) removed the depression for both nozzles tested.

Altitude Blowout and Relight

These tests were run only with the showerhead gas nozzles. The data are presented in figure 10. With ambient temperature fuel the combustor blowout limit was 6.0 N/cm^2 (8.7 psia); relight was not obtained until the pressure was raised above 12.1 N/cm^2 (17.5 psia). With heated fuel at 800 K (980° F), the blowout limit was reduced to 3.45 N/cm^2 (5.0 psia). The combustor relit (not spontaneously) at this pressure, indicating that a substantial improvement in relight capability is possible compared to ambient-temperature fuel conditions.

CONCLUDING REMARKS

The data taken with the pintle fuel nozzles indicate that significant improvements in combustion efficiency at off-design conditions can be obtained by heating the fuel if the combustion instability can be eliminated. This may be accomplished by redesign of the air swirler and fuel injector. Improvement would probably come from a larger pintle area and lower fuel injection velocity. These changes would increase the recirculation zone behind the fuel injector and provide increased flame seating stability. The modifications would require that the air swirler diameter be increased, but no increase in airflow through the swirler is recommended.

Data taken with the showerhead fuel nozzles indicate that combustion was stable over all test conditions but that only moderate improvements in combustion efficiency were obtained by heating the fuel. The combustion efficiency of this nozzle could possibly be improved if the fuel injection location was not downstream of the air swirler, as it is presently configured. Also, the large nozzle diameter interferes somewhat with the operation of the air swirler. The air swirler should be redesigned with a larger diameter to be compatible with the fuel nozzle.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 28, 1972,
501-24.

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TABLE I. - PHYSICAL PROPERTIES OF NATURAL GAS

Density[a], kg/m^3 (lb/ft^3)	0.7320 (0.0457)
Net heat of combustion (calculated), J/kg(Btu/lb)	4.977×10^7 (2.140×10^4)
Normalized chromatographic analysis (calculated), vol. %:	
Methane	93.50
Ethane	3.53
Propane	0.53
Hydrocarbons (C_4, C_5, C_6)	0.32
Nitrogen	1.05
Carbon dioxide	1.07
Oxygen	Trace

[a]Density in kg/m^3 is at 289 K (1.02×10^5 N/m^2 at 273 K). Density in lb/ft^3 is at 60° F (30 in. Hg at 32° F).

TABLE II. - COMBUSTOR NOMINAL OPERATING CONDITIONS

Operating condition	Combustor inlet				Airflow rate		Reference velocity		PT/V parameter		Diffuser inlet Mach number
	Pressure		Temperature		kg/sec	lb/sec	m/sec	ft/sec	(N)(K)(sec)/m^3	(lb)($^\circ$R)(sec)/ft^3	
	N/cm^2	psia	K	$^\circ$F							
1	17.2	25.0	422	300	20.6	45.5	32.3	106	22.53×10^5	25.81×10^3	0.326
2	13.8	20.0	422	300	20.6	45.5	40.5	133	14.36	16.46	.415

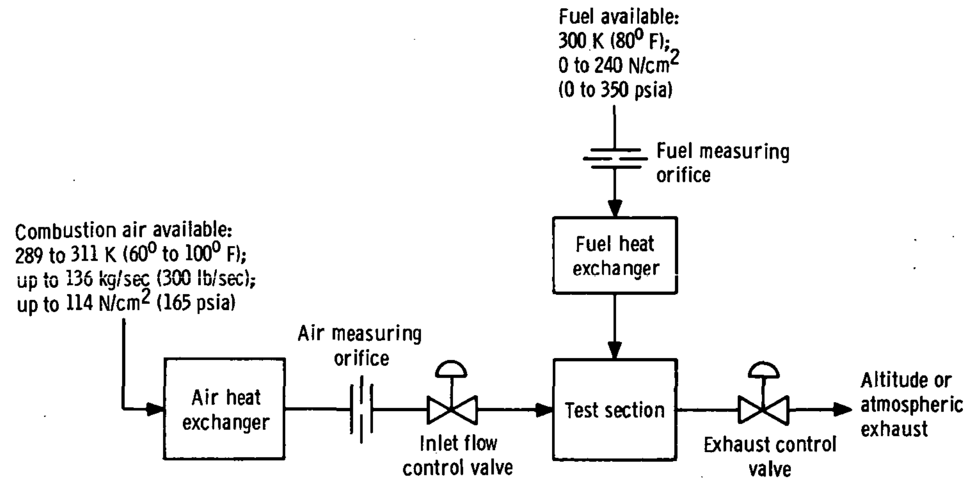


Figure 1. - Test facility.

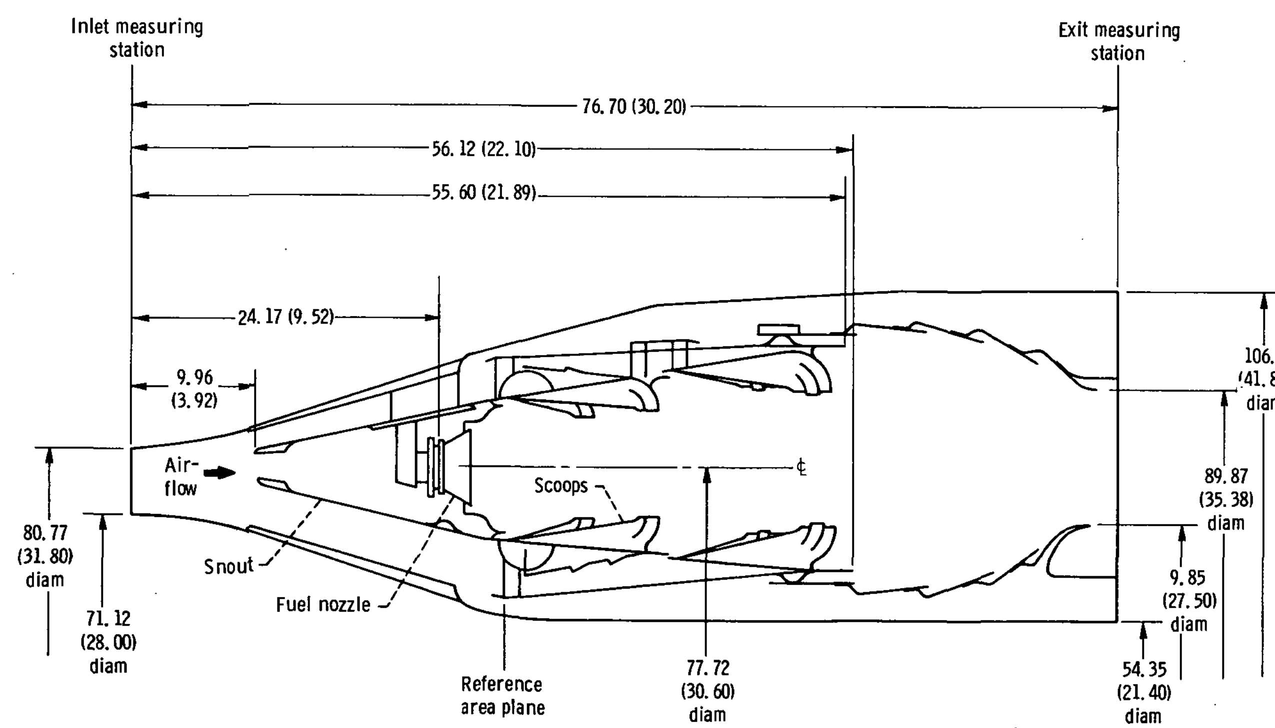
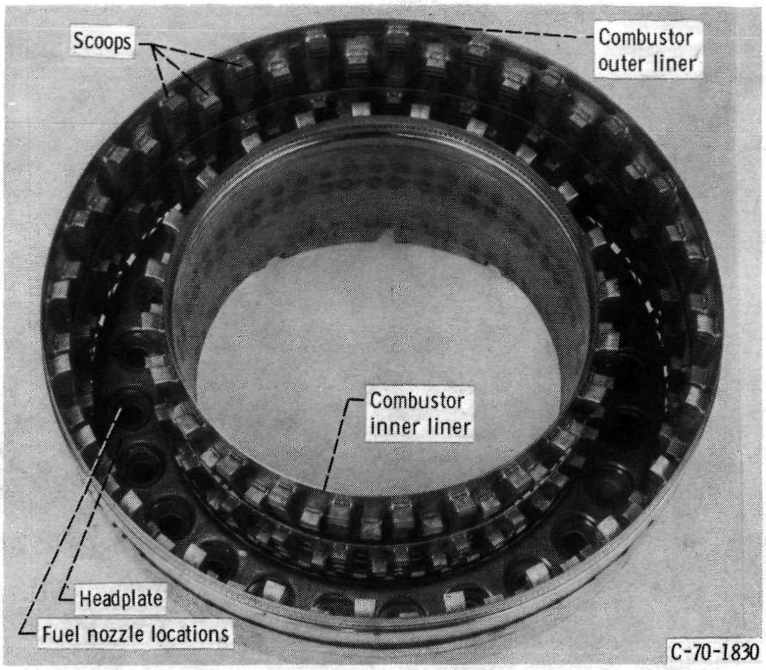
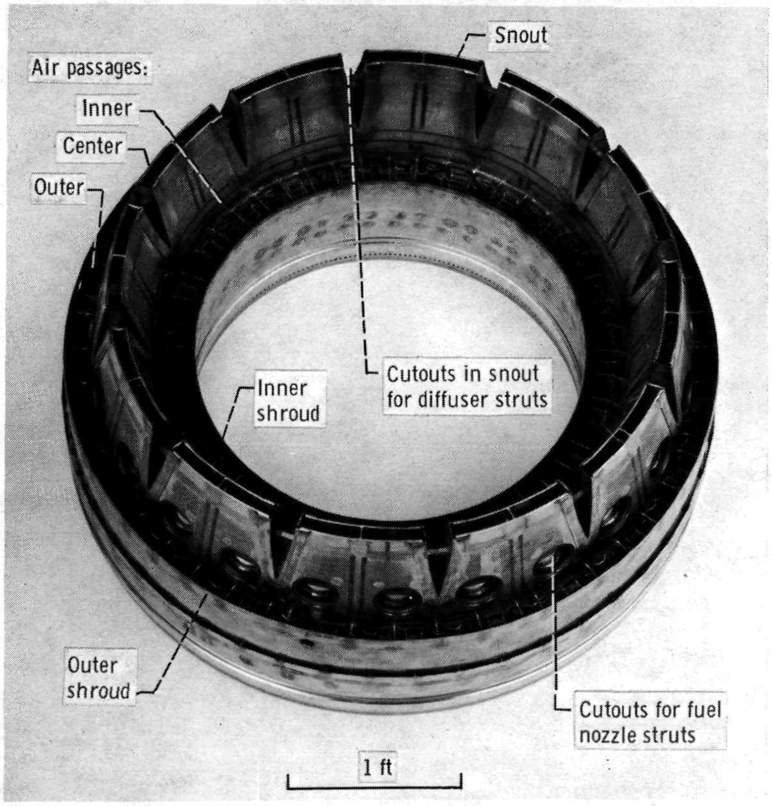


Figure 2. - Cross section of combustor. Dimensions are in cm (in.).

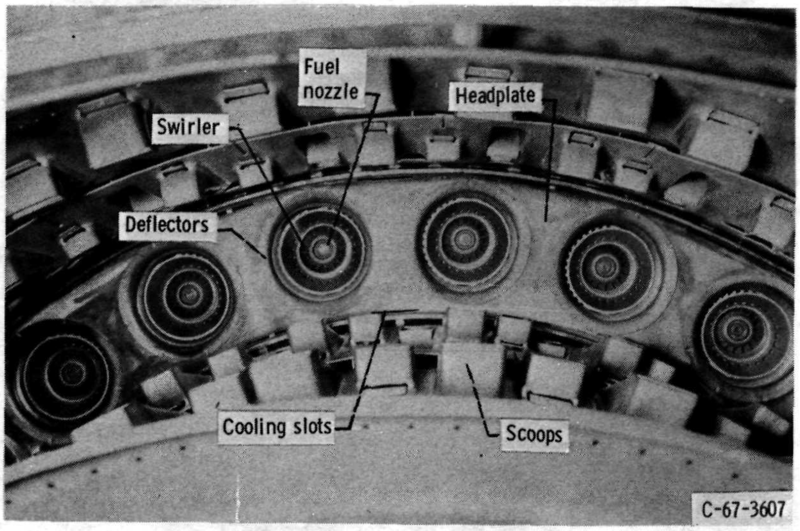


(a) View from downstream end.



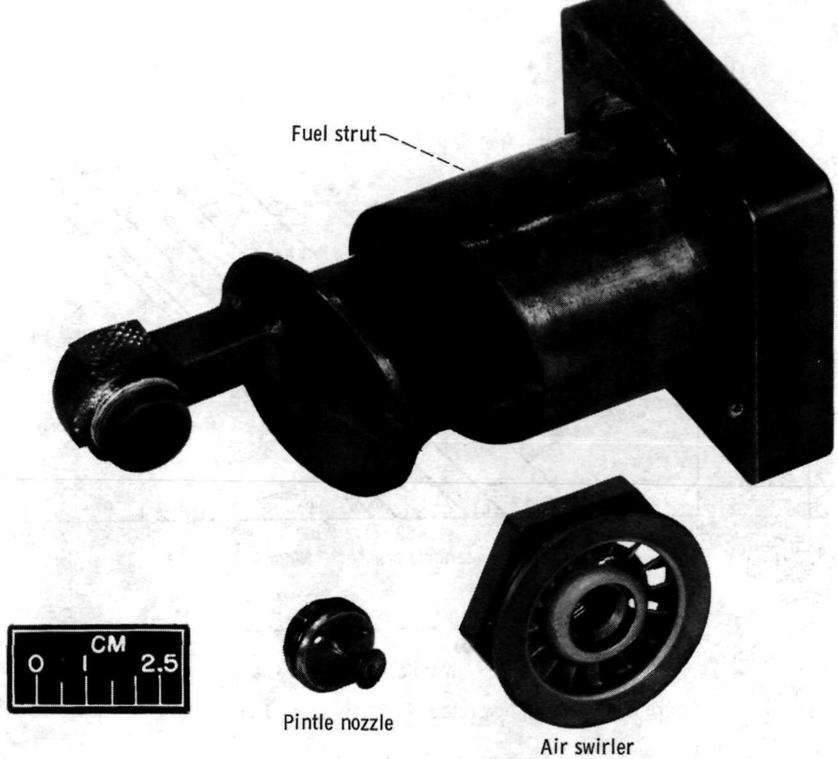
(b) View from upstream end.

Figure 3. - Annular ram-induction combustor.

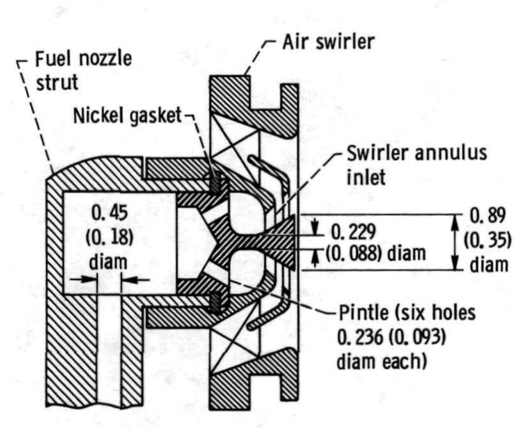


(c) Closeup view from downstream end.

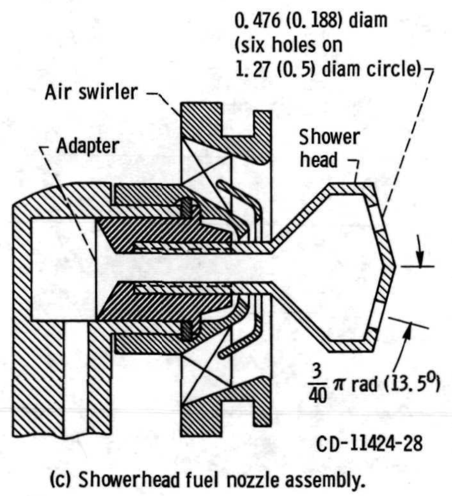
Figure 3. - Concluded.



(a) Gas fuel strut, nozzle, and swirler.



(b) Pintle fuel nozzle assembly.



(c) Showerhead fuel nozzle assembly.

Figure 4. - Gaseous fuel nozzle assemblies. Dimensions are in cm (in.).

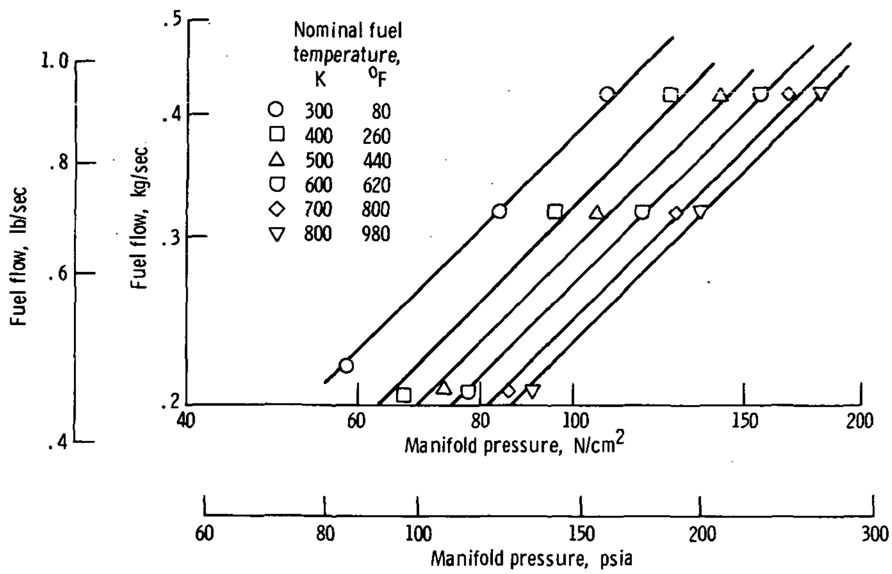
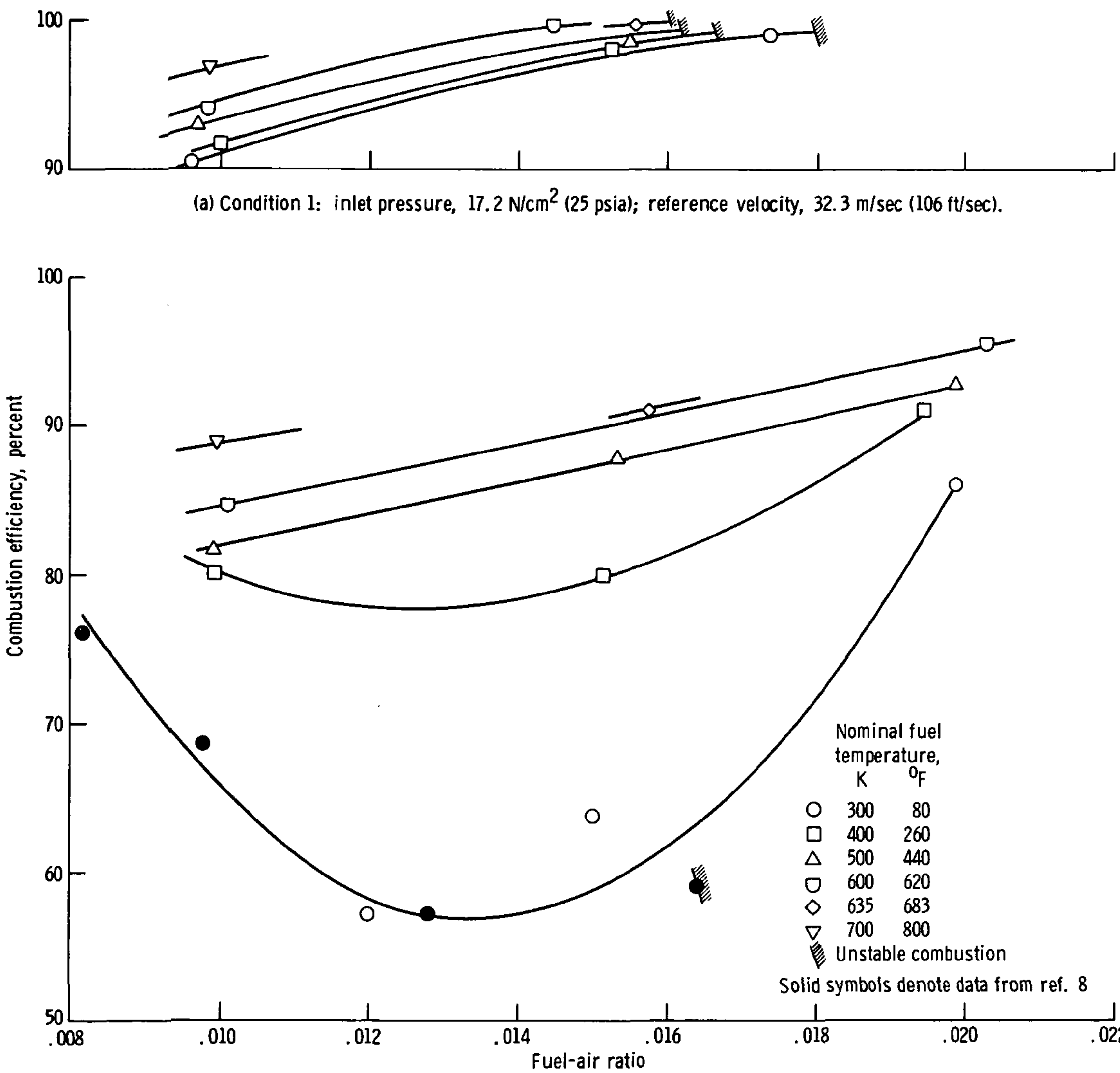
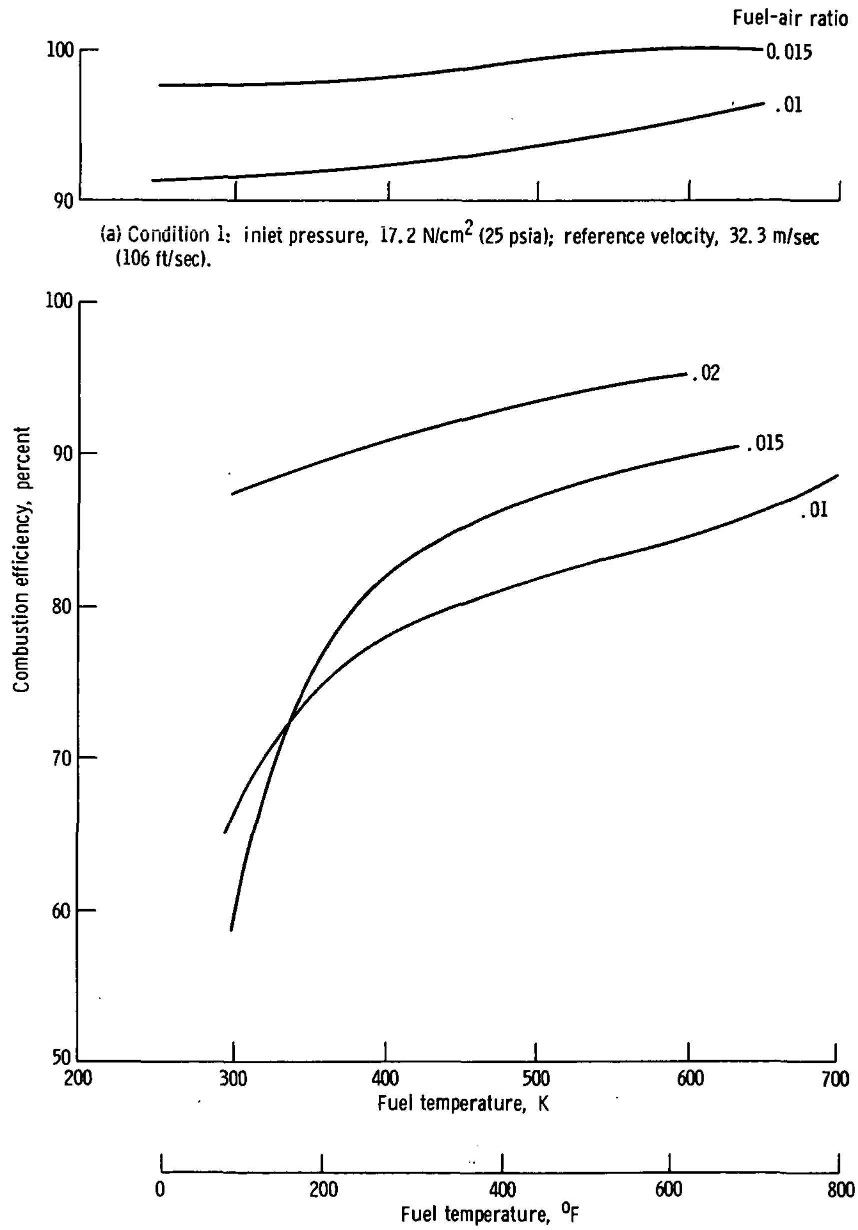


Figure 5. - Total fuel flow rate as function of manifold pressure.



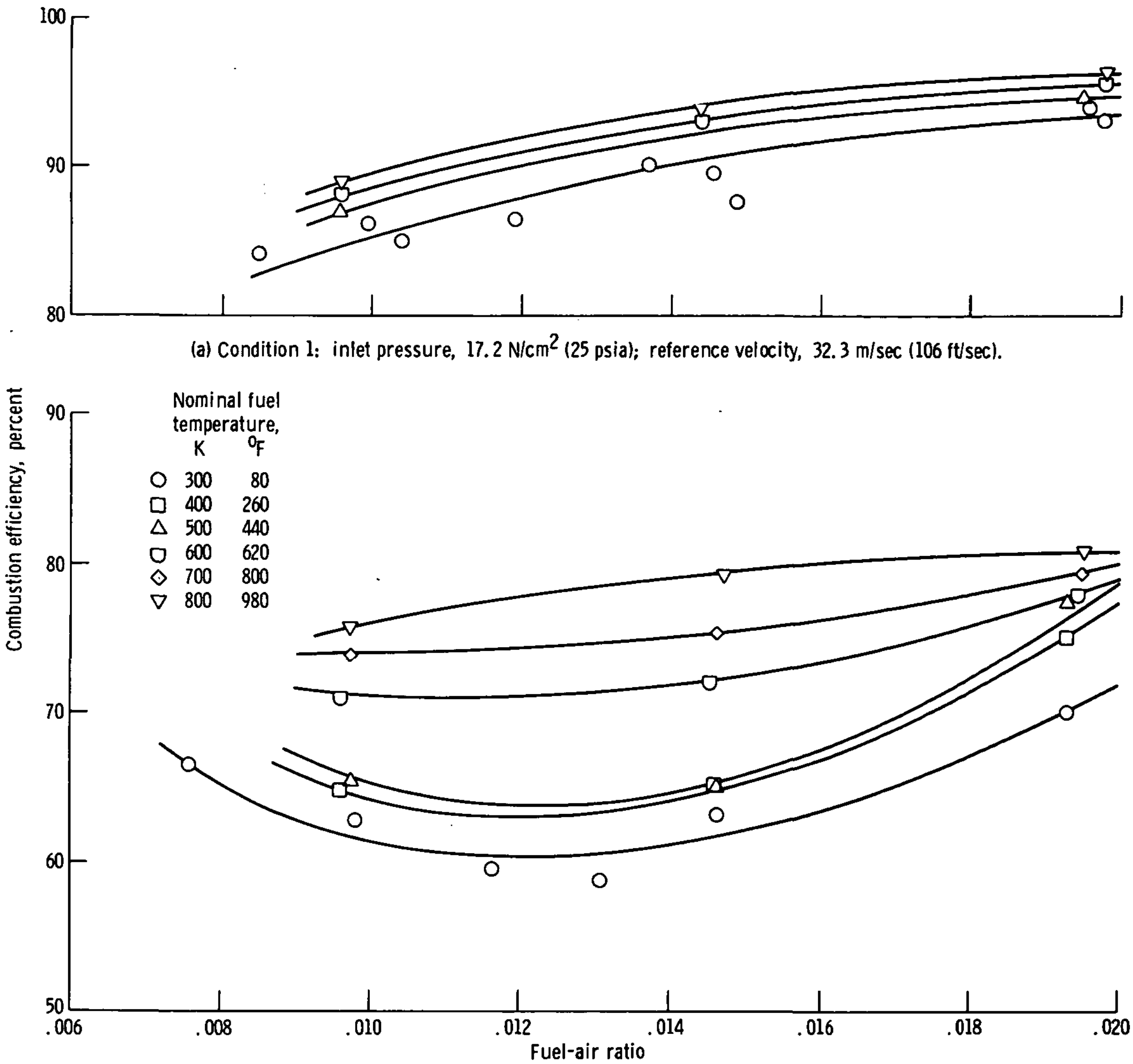
(b) Condition 2: inlet pressure, 13.8 N/cm^2 (20 psia); reference velocity, 40.5 m/sec (133 ft/sec).

Figure 6. - Combustion efficiency as function of fuel-air ratio and fuel temperature - pintle nozzle.



(b) Condition 2: inlet pressure, 13.8 N/cm^2 (20 psia); reference velocity, 40.5 m/sec (133 ft/sec).

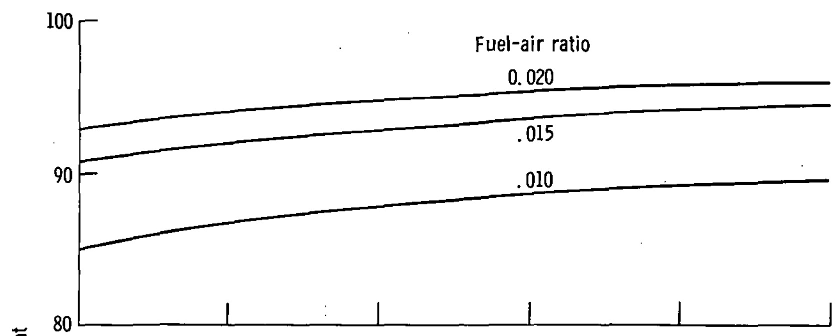
Figure 7. - Combustion efficiency as function of fuel temperature - pintle nozzles.



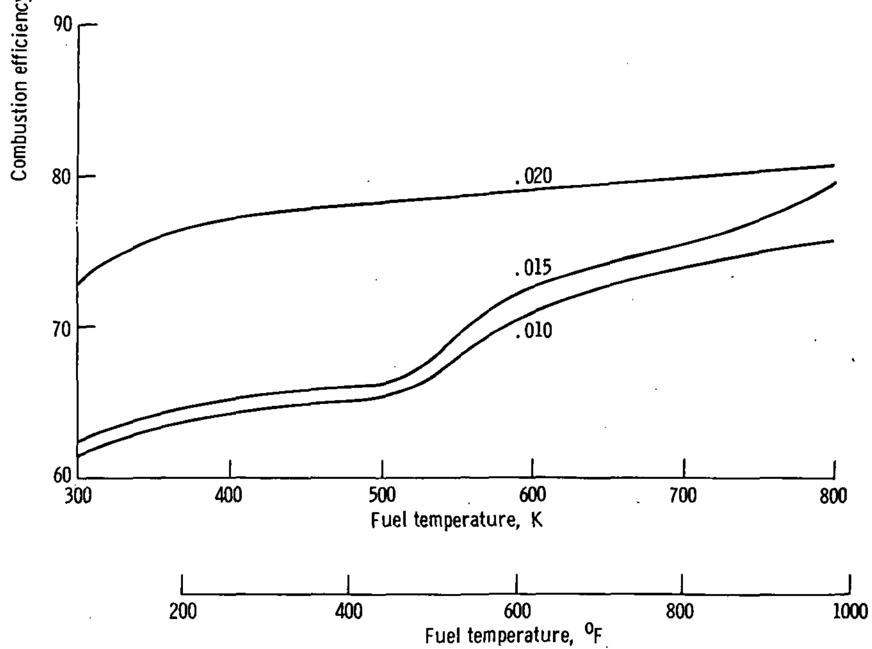
(a) Condition 1: inlet pressure, 17.2 N/cm^2 (25 psia); reference velocity, 32.3 m/sec (106 ft/sec).

(b) Condition 2: inlet pressure, 13.8 N/cm^2 (20 psia); reference velocity, 40.5 m/sec (133 ft/sec).

Figure 8. - Combustion efficiency as function of fuel-air ratio and fuel temperature - showerhead nozzles.



(a) Condition 1: inlet pressure, 17.2 N/cm^2 (25 psia); reference velocity, 32.3 m/sec (106 ft/sec).



(b) Condition 2: inlet pressure, 13.8 N/cm^2 (20 psia); reference velocity, 40.5 m/sec (133 ft/sec).

Figure 9. - Combustion efficiency as function of fuel temperature - showerhead nozzles.

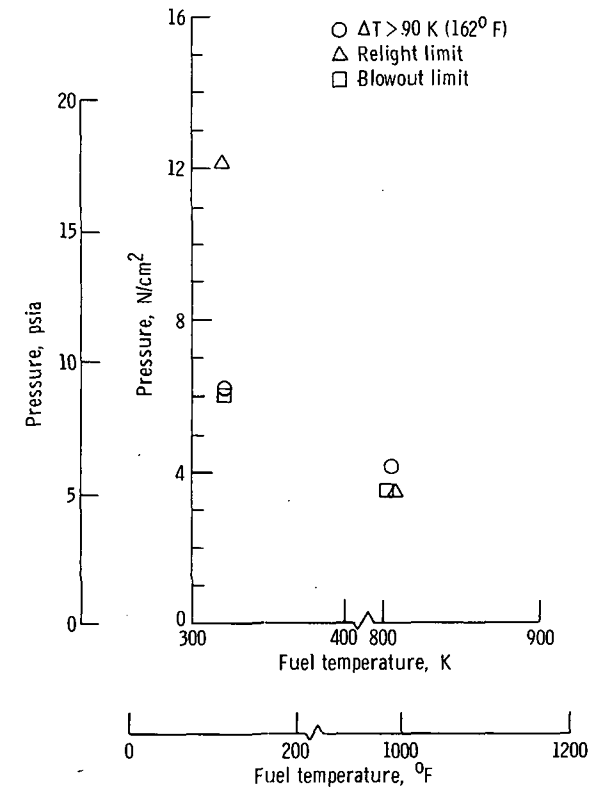


Figure 10. - Altitude and relight characteristics of showerhead nozzles at fuel temperatures near 300 K (80^0 F) and 800 K (980^0 F). Inlet-air temperature, 300 K (80^0 F); reference Mach number, 0.075.

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